PHOSPHORUS AS A POLLUTANT IN SURFACE WATERS

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Phosphorus is one of the essential nutrient elements required by both land and water plants. It is absorbed by plants largely as the primary and secondary orthophosphate ions (H_2PO_4- and HPO_4 $=$). Very small quantities of soluble organic phosphate also may be absorbed.

The concentration of soluble phosphate ions in most soils is seldom large enough to adversely affect plant growth. Hence phosphorus in soils is not considered a pollutant. More commonly the concentration of phosphate ions in soils is too low for optimum crop yields and fertilizers containing phosphate must be applied to produce the food and fiber required by man.

Phosphorus concentrations in surface waters, on the other hand, often are large enough to cause excessive algae growth. Excessive algae growth is undesirable because it makes rivers and lakes less suitable for recreation and increases water purification costs. Because the concentration of phosphorus in surface waters frequently is the limiting factor for the growth of algae and aquatic weeds, it is considered a pollutant by ecologists when the concentration exceeds 0.01 to 0.05 part per million. Ecologists claim that such concentrations of phosphorus permit profuse growth of algae under conditions where other growth factors such as light, other essential elements, toxic substances, temperature, acidity, carbon dioxide content, and oxygen supply are not limiting.

Sources of phosphorus in surface waters have been listed as originating from precipitation, aquatic life, underwater sediments, human food wastes, household detergents, industrial wastes, animal wastes, phosphorus fertilizers and runoff from forest, rangeland, urban and field soils. The contribu-

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tion of each source to the phosphorus content of surface waters in North Dakota is unknown. Inasmuch as leaching and runoff may occur from soils, soil is one of the sources of phosphorus in surface waters.

Phosphorus can be transported to surface waters by three mechanisms: (a) in solution by leaching, (b) in solution by runoff, and (c) in sediments carried by runoff. Only small amounts of phosphorus are lost by leaching because one of the most striking characteristics of native soil phosphate and fertilizer phosphorus is immobility. Practically all phosphorus applied in soluble form is converted to water-insoluble compounds within a few days. These compounds are chemically similar to the native soil phosphates. Furthermore, phosphorus adsorption by soil solids and uptake by plants and microorganisms tend to restrict the downward movement of phosphorus in percolating waters. Hence, phosphorus accumulates in surface soils after continued application of fertilizers and only small amounts are lost to ground waters by leaching.

Concentrations of phosphorus in soil saturation extracts of midwestern soils and in draintile outflows in Ontario are presented in Tables 1 and 2, respectively. Note that the annual losses of phosphorus by leaching and draintile outflow in Ontario were less than 0.26 kg P/ha. (kg/ha times 0.9 equals pounds per acre.) Fertilizer at a rate of 336 kg/ha/year of 5-20-10 has increased leaching losses by only 0.07 kg P/ha/yr.

Data from the midwestern states also indicates relatively low concentration of phosphorus in saturation extracts. The mode of the frequency distribution was 0.04-0.06 ppm. At this concentration, an acre-foot of water passing through the soil or over the soil would remove only about 0.16 pounds

Table 1. A frequency distribution of P contents of saturation extracts measured on mid-western United States soils.[1]

P in saturation extract, ppm	Number of soil samples
0.02 - 0.04	4
0.04 - 0.06	23
0.06 - 0.08	31
0.08 - 0.10	28
0.10 - 0.12	9
0.12 - 0.14	10
0.14 - 0.16	9
0.16 - 0.18	8
0.18 - 0.20	1
0.20 - 0.21	1
0.21 - 0.40	11
0.41 - 0.60	3
0.61 - 0.80	2
0.81 - 1.00	1
1.01 - 1.20	1

[1]S. A. Barber, J. M. Walker, and E. H. Vasey. New Zealand Intern. Soils Conf. Proc. 3, 1962.

Table 2. Average annual losses and concentrations of phosphorus through draintiles on Brookston Clay (1961-1967).[1]

Crop Rotation:	P losses Kg/ha/year No Fert	Fert.	P concentration ppm No. Fert	Fert.
Corn	0.13	0.24	0.20	0.22
Oats + Alfalfa	0.13	0.13	0.20	0.19
Alfalfa 1st yr.	0.13	0.15	0.18	0.21
Alfalfa 2nd yr.	0.08	0.22	0.17	0.27
Continuous:				
Corn	0.26	0.29	0.17	0.19
Bluegrass sod	0.01	0.12	0.17	0.19
Mean	0.12	0.19	0.18	0.21
S.E.	0.03			

[1]Bolton, E. F., et al. Canadian Jour. Soil Sci. 50:275-279. 1970.

of phosphorus. In North Dakota, where the annual precipitation ranges from 13 to 20 inches per year, leaching is not a problem except possibly in the coarser textured soils.

Thus, surface runoff is the major mechanism by which phosphorus is transported from rangeland, forest, urban and rural soils to surface waters. Runoff phosphorus may exist in a dissolved state or be present as suspended particulates which eventually merge with and become part of the stream and/or lake sediments. The amount of sediment in runoff waters may be small or large, depending upon slope, soil type, vegetation and nature of the precipitation. According to the 1955 USDA Yearbook of Agriculture, "Water", average annual runoff is one inch or less in North Dakota.

Amounts of water soluble phosphorus removed by snowmelt and rainfall runoff from Barnes loam in Morris, Minnesota, are presented in Table 3.

Table 3. Annual phosphorus losses in runoff water and sediment from snowmelt and rainfall for two seasons on 6 per cent sloping Barnes loam at Morris, Minnesota.[1]

Cropping Treatments	Phosphorus losses, lbs/acre: Snowmelt H_2O	Snowmelt Sediment	Rainfall H_2O	Rainfall Sediment
1966				
Fallow	0.03	0.01	0.03	0.14
Corn-continuous	0.	0.	0.05	0.03
Corn-rotation	0.03	0.	0.03	0.02
Oats-rotation	0.	0.	0.	0.
Hay-rotation	0.06	0.	0.	0.
1967				
Fallow	0.01	0.03	0.02	0.42
Corn-Continuous	0.01	0.	0.06	0.16
Corn-rotation	0.04	0.	0.02	0.05
Oats-rotation	0.01	0.01	0.01	0.05
Hay-rotation	0.34	0.	0.01	0.

[1]D. R. Timmons et al. Minnesota Science, Vol. 24, No. 4, Summer 1968.

Note that snowmelt from the hay rotation in 1967 removed 0.34 pounds of phosphorus per acre in solution. Leaching of phosphorus by snowmelt from frozen and thawed hay samples can contribute an appreciable amount of phosphorus to surface waters. This also may have been an important source of P to water before grasslands were cultivated. Also note that phosphorus losses in sediment were highest from fallow plots, but losses in runoff water were highest from rotation corn and hay plots. Much of the phosphorus lost in runoff waters from hay and corn rotation plots was in snowmelt runoff.

Annual losses of soil and phosphorus per acre at Morris, Minnesota, are presented in Table 4. Note that hay rotation reduced soil losses and that greatest soil and phosphorus losses occurred on fallow plots.

Table 4. Annual soil and phosphorus losses from Barnes loam based on 1961-1967 soil losses and 1966-67 phosphorus losses at Morris, Minnesota.[1]

Cropping Treatments	Avg. Annual Tons/Acre Soil loss	Avg. Annual lbs P loss per ton soil loss	Avg. Annual lb/Acre of P loss
Fallow	21.37	0.05	1.07
Corn-continuous	9.44	0.09	0.85
C-O-H rotation	2.21	0.39	0.86

[1]D. R. Timmons et al. Minnesota Science, Vol. 24, No. 4, Summer 1968.

Manure is lost from frozen fields by snowmelt runoff and from feedlots throughout the year by sporadic runoff. These rains and snowmelts flush large amounts of manure into streams. Most of the phosphorus from animal wastes is in solid organic form, with probably about five per cent in the liquid form. Organic material from animal wastes not only transports phosphorus and other elements, but also readily depletes dissolved oxygen in streams when it undergoes aerobic decomposition. This oxygen deficiency can be serious enough to kill fish. The Big Stone Lake study in 1967 reported that about 20 to 25 per cent of the phosphorus entering that lake originated from cattle feedlots adjacent to the lake or its streams.

Amounts of phosphorus added to surface waters by natural sources may also be appreciable. Precipitation, underwater sediments, aquatic life and runoff from rangeland and forests are the principal natural sources. In 1968, F. Alan Ferguson of the Stanford Research Institute estimated that as much as 41 per cent of the phosphorus entering United States waters could come from natural sources. Natural erosion also contributes appreciable amounts of sediments to surface waters. As evidence of natural waters that have deteriorated without the help of man, one only has to observe the many acres of peat and muck and the extent of our coal and oil deposits. These were all formed by natural processes many years ago.

Runoff soil particles, regardless of origin, may add or remove phosphorus from runoff waters, streams and lakes. Whether or not eroded soil particles add or remove phosphorus from the waters depends on a number of variables, among which are the phosphorus content of the water and the nature of the phosphorus on or in the eroded soil particles. If the phosphorus content of the water is in the order of 1 ppm, then most soil particles suspended in such waters will remove phosphorus from the solution. On the other hand, if the phosphorus content of the water is extremely low, say less than 0.01 ppm, then most suspended soil particles will add phosphorus to the water. Even soil particles from many nonfertilized soils may release enough phosphorus to pure water so the concentration of the equilibrium water is sufficient to permit profuse algal growth.

Data obtained by Anande and Moraghan and by Dahnke support the hypothesis that soil sediments may remove or add phosphorus to the solution (Tables 5 and 6). When the phosphorus concentration in solution was 0.45 ppm or greater, all soils removed phosphorus from solutions. At 0.01 ppm, six soils removed phosphorus, two soils caused no change, and two soils added phosphorus to the solution. Table 6 also shows that soils testing very low

Table 5. P contents of soil solutions of selected North Dakota soils after treatment with 0.01 M $CaCl_2$ containing various amounts of added P.[1]

Soil	pH	$NaHCO_3$ Soluble P Lbs/A	P added, ppm in solution[2] 0	0.10	0.45	0.80	1.00
			P in Soil Solution, ppm				
Tiffany fsl	7.6	18.0	0.20	0.20	0.21	0.38	0.45
Gardena vfsl	8.3	4.0	0.06	0.07	0.10	0.29	0.32
Gardena vfsl	8.4	3.0	0.05	0.05	0.05	0.06	0.08
Gardena vfsl	8.5	6.1	0.05	0.09	0.13	0.20	0.22
Gardena sl	7.1	11.9	—	0.12	0.12	0.36	0.38
Hecla lfs	6.7	15.9	0.01	0.10	0.16	0.28	0.31
Hecla fsl	7.1	6.0	0.10	0.09	0.20	0.28	0.41
Hecla fsl	7.8	3.9	0.03	0.04	0.04	0.05	0.13
Moddox fs	6.6	4.0	0.07	0.10	0.14	0.25	0.39
Fargo scl	6.4	10.0	0.04	0.04	0.05	0.07	0.08

[1]S. Anande and J. Moraghan, unpublished data.
[2]Soil: solution ratio was 1:10. Shaking time was 17 hours.

Table 6. Change in P contents of solutions after shaking 1 gram of soil with 100 ml of 0.2 ppm P solution for 1 day.[1]

Gain or loss of P, ug P/100 ml	Number of soils for each test level:[2] Very low	Low	Medium	Very high
+6	—	—	—	2
+5 to +6	—	1	1	—
+3 to +4	—	1	—	—
+1 to +2	1	1	3	—
No change	—	2	1	—
−1 to −2	1	—	—	—
−3 to −4	1	3	—	—

[1]Dr. W. C. Dahnke, unpublished data.
[2]Test level by 0.5M $NaHCO_3$ procedure used at NDSU.

in phosphorus removed phosphorus from solutions containing 0.2 ppm and that medium and very high testing soils added phosphorus to the solution. Thus it is probable that the phosphorus content of streams or runoff water may differ at different points as a result of the different kinds of soil or sediment contained in the water.

Most soils in North Dakota do not contain enough of the more soluble forms of phosphorus for optimum crop yields. The soil testing laboratory analyzes soil samples specifically to determine how much fertilizer phosphorus to add to each soil for increasing crop yields. The summary of phosphorus soil test values is presented in Table 7. Note the large proportion of soils that test very low and low. Sediments from the low and very low phosphorus soils most likely will not add phosphorus to the solution in excess of about 0.1 to 0.2 ppm. Soil sediments from medium to high testing soils may add phosphorus to the solution to bring the concentration up to about 0.3 ppm.

Table 7. Soil test summary for phosphorus by state and areas.[1]

Area	Period	No. of Samples	Per cent in each P test rating: VH	H	M	L	VL
State	9/1953 - 6/1969	85,381		9	25	20	46
State	7/1968 - 6/1969	4,193		13	18	19	50
State	7/1969 - 6/1970	5,341	4	14	23	21	38
State	7/1970 - 11/1970	2,206	7	12	22	28	31
RRV	7/1969 - 11/1970	1,383	10	18	23	25	24
East Central	7/1969 - 11/1970	3,190	3	11	23	25	38
West Central	7/1969 - 11/1970	1,529	3	10	22	22	43
West	7/1969 - 11/1970	1,446	5	18	25	19	33

[1]R. A. Torkelson, and W. C. Dahnke, unpublished data.

As erosion removes surface soils, sediments from subsoils and possibly from stream channels and river banks contain lower amounts of soluble forms of phosphorus. Table 8 presents the amounts of sodium bicarbonate extractable phosphorus present in horizon samples of seven common soil series in North Dakota. Note the large amounts of phosphorus in the A1 horizon (surface soil) as compared to the remaining soil horizons. The data in Table 9 also show that the phosphorus soil test level for surface soils was about 2.5 times greater than for subsoils. Thus subsoils and stream banks may not add very much dissolved phosphorus to water but may remove phosphorus from water containing more than about 0.1 ppm.

Table 8. Amount of phosphorus extracted by the sodium bicarbonate procedure from horizon samples of selected North Dakota Soils.[1]

Soil Series	$NaHCO_3$ Extractable P from soil horizon, ppm A1	A2	B2	Cca	C
astad	12.4	—	1.9	0.1	0.5
arnes	5.3	—	1.3	1.7	1.8
amerly	12.0	—	—	0.7	0.3
etonka	36.1	22.0	12.3	—	—
rnegard	11.0	—	2.0	2.8	—
orton	5.8	—	2.0	2.6	2.2
illiams	12.6	—	2.9	2.7	2.0

[1]Data obtained by J. C. Zubriski and submitted for publication in Agron. Jour., 1970.

Table 9. Ratio of surface soil phosphorus test values to subsoil phosphorus test values for 1970.[1]

Area	0-6"/6-24" ratio	6-24: as % of 0-6"
RRV	2.6:1	38%
East Central	3.1:1	32%
West Central	2.3:1	43%
West	1.8:1	54%
State	2.5:1	39%

[1]R. A. Torkelson and W. C. Dahnke, unpublished data. Data represent 314 random samples obtained in 1970.

SUMMARY

Many soils of North Dakota contain inadequate amounts of phosphorus to produce optimum crop yields. Applying phosphatic fertilizers is one of the main ways to increase crop yields on these soils.

Runoff and sediment delivery are the major modes of transporting phosphorus to surface water. From the limited data available, it appears that the content of phosphorus in waters equilibrated with sediments from most surface soils will contain sufficient amounts of phosphorus to support profuse algae growth. Good soil management practices that prevent erosion are the most effective means of reducing the movement of phosphorus into surface waters.

Sources other than from agricultural endeavors may contribute more than adequate amounts of phosphorus to surface water to cause accelerated eutrophication. Under these circumstances, reducing inputs of phosphorus from agricultural sources may have little impact on retarding eutrophication.

A research program to identify sources and amounts of phosphorus entering streams and lakes of North Dakota is necessary before sound control measures can be proposed and evaluated. Inasmuch as most phosphorus enters waters from agricultural soils in runoff waters, the extent of sediment erosion and amount of runoff from major soil associations under various cropping patterns must be documented. Our knowledge is limited of phosphorus distribution between that in solution and that adsorbed on soil particles of various kinds. Examination of the adsorption and release of the phosphorus from the various sediments is needed to provide information on the role of sediment-phosphorus interactions in eutrophication.